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Estimation of Settlements of Bored Piles Foundation

Linas Gabrielaitis[a,*], Vytautas Papinigis[b], Gintaras Žaržojus[c]

[a, c]*Vilnius Gediminas Technical University, Faculty of Civil Engineering, Department of Geotechnical Engineering, Saulėtekio al. 11, Vilnius LT-10223, Lithuania*
[b]*Vilnius Gediminas Technical University, Faculty of Civil Engineering, Department of Reinforced Concrete and Masonry Structures, Saulėtekio al. 11, Vilnius LT-10223, Lithuania*

Abstract

The paper describes the estimating settlements of bored piles foundation on the site of the Elektrenai power plant, Lithuania. The bored piles foundation supports equipment of the power plant consisting of the gas turbine, the steam turbine and the generator. The piling solution was adopted for the following reasons: i) the insufficient capacity of the soil to support great stresses over it; ii) high requirements of slab settlements and bearing capacity with regard to the main equipment in power plant.). For settlement calculation five methods were employed, such as Bowles [1] and Schmertmann methods [2–3], the method described in EN 1997-2 [4–6] and NEN 6743 [7], and finite element method applied in Plaxis 3D Foundation package. The results obtained by applying these methods where compared with experimental results on construction site. The experiment results were acquired from static load test of one test pile and four reaction piles.

Piled foundation was evaluated through immediate settlement analysis and included analysis of the soil data from cone and dynamic penetration tests, boreholes and laboratory tests. Soil properties were estimated from site investigation of the Elektrenai power plant and soil exploration program according to Lithuanian standards. Pile settlement analysis showed that settlement value was 13.5 mm (pile toe settlement), and settlement value of elastic deformation of pile from vertical compressive loads was 2.1 mm, for the most conservative situation. For such structure, foundation settlement should not exceed 16 mm. Because the Elektrenai power plant has high reliability requirements, piles diameter of 880 mm and 29 m long were finally carried out to endure overall loads.

Nomenclature

A	area of pile cross section (m^2)
D	pile diameter (m)
Q	maximum applied load at pile head (kN)
L	pile length (m)
q	bearing pressure at point (kPa)
E_p	elastic modulus of pile (MPa)
E_s	stress-strain modulus of the soil (MPa)
I_F	embedment factor
F_1	reduction factor

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* Corresponding author. Tel.: +370-61012217.
E-mail address: [a]linas.gabrielaitis@vgtu.lt

mI_s	shape factor
s_d	immediate pile settlement (mm)
$s_{toe,d}$	pile toe settlement (mm)
$s_{el,d}$	pile elastic compression settlement (mm)
Greek symbols	
γ	stoichiometric coefficient
φ'	shearing resistance (°)

1. Introduction

Foundation settlements must be estimated with great care for buildings, towers, power plants, and similar high-cost structures. Except for occasional happy coincidences, soil settlement computations are only best estimates of the deformation to expect when a load is applied. During settlement the soil transitions from the current body (or self-weight) stress state to a new one under the additional applied load [1]. The statistical accumulation of movements in the direction of interest is the settlement. A major factor that greatly complicates foundation design is that the soil parameters have to be obtained on construction site prior the project calculation.

The prediction of pile settlements can be achieved as a sum of a pile heel settlement and elastic deformation of pile. Settlement analysis plays an important role in building foundation, even though only few modern buildings collapse from excessive settlements, it is not uncommon for a partial collapse or a localized failure in a structural member to occur [8]. Excessive settlement and differential movement can cause distortion and cracking in structures [9] especially for rotary machines which are particularly sensitive to bearing misalignment. In other words, the adequacy of the adopted state-of-the-art design method may greatly reduce the risk factor of settlement problems without unduly raising foundation costs.

The scope of this work is to design the pile foundation that is required for gas and steam turbine equipment on the site of the Elektrenai power plant, Lithuania.

The current work consists of four parts:
1. To assess immediate settlement employing analytical Bowles method
2. To assess immediate settlement employing three methods, such as Schmertmann, EN 1997-2 and NEN 6743
3. To assess immediate settlement employing finite element method that is applied in Plaxis 3D Foundation package
4. To compare the experimental results obtained from static load pile test with the computation results obtained by employing above mentioned methods

In this work, the deep pile foundation was designed to sustain loads from gas and steam turbine equipment on the site of the Elektrenai power plant, Lithuania. In the design of a pile foundation, the required pile length was estimated based on the load from the superstructure, allowable stress in the pile material, and the in situ soil properties Soil properties were estimated from site investigation and soil exploration program according to Lithuanian regulations. Investigation data were based on cone penetration and dynamic penetration tests, boreholes, excavations and soil as well as laboratory investigations. From these data, four geological layers were generalized that were applied in design of pile foundation.

Pile settlement analysis estimated that total settlement value was 15.6 mm, including 2.1 mm settlements of elastic deformation of pile from vertical compressive loads. In general, pile settlement should not be more than <2%D (where D is a diameter of the pile). Such settlement criteria was taken according to guidelines for shallow or piled foundations settlement from IEC (Iberdrola Engineering and Construction) [10], which states the limits for absolute and differential settlements in the operational phase and are mainly focused on the long-term settlements.

2. Pilling foundation consideration

Piled foundation was chosen for gas turbine structure and other equipment due to two different reasons:
- The capacity of the soil to undergo great stresses. In other words, bearing capacity of soils represents the ability of soil to safely carry the pressure placed on the soil by piles without undergoing a shear failure with accompanying large settlements
- The special requirements of the main equipments about settlements bearing capacity. The equipment consisted of the gas turbine, the steam turbine and the generator. The generator is coupled to the gas turbine through a rigid coupling and is connected to the steam turbine by a flexible coupling. The equipment induces high loads, which, in turn, induces great stresses on the foundation. The combined unit of gas turbine, generator and steam are founded on a single slab foundation, which has to provide the adequate resistance and comportment for all the static and dynamic equipment conditions

As the main purpose of the foundation is to receive the loads from the equipments and to transmit these loads to the piles, it should satisfy settlement and dynamic criteria. According to analyses of the stresses induced by the loads, the gas and steam turbine equipment required deep pile foundation. The design of a deep pile foundation has three main steps, ordered as follows**:**

1. Determination of DWL (design working load) and SWL (safe working load) for a single pile, based on the structural characteristics (SWL is the basic design load)
2. To obtain bearing capacities and related settlements for several pile lengths, according to the geotechnical subsoil parameters at site (coming out from all soil and lab tests, not only CPT). Here, the lowest required pile length is chosen, for the optimal bearing capacity (the closest above SWL) with acceptable settlement

To check the actual behavior of several grids of piles under the foundation slab, in order to get the most uniform load distribution at the pile heads, the closest below SWL, minimizing the number of piles but also guaranteeing uniform slab settlement, minimum differential settlements between piles and consequently, minimizing settlement induced stresses in the slab.

For the design deep piles foundation, the required pile length (for a given pile diameter) was estimated from the superstructure loads, allowable stress in the pile material, and the in situ soil properties. It was based on the following steps [11–12]:

1. Soil properties were determined from site investigation and soil exploration program according to IEC [10] and Lithuanian regulations
2. Superstructure loads were obtained from the manufacturer of gas and steam tribune, and described in publication [12] It included design verification load of 2500 kN and service working load of 2239 kN
3. The bored cast-in-place piles were adopted of diameter 880 mm that rested on the very dense sandy bed. Based on the data from previous two steps, estimation of pile length was performed along the pile carrying capacity and settlements

The steps 1 and 3 are described in the following sections, since the computation of settlements of bored piles foundation of superstructure is the main purpose of this work. Whiles the computation of carrying capacity of bored piles was comprehensive analyzed in previous works [11–12].

3. Physical and mechanical properties of the soil

Soil properties were determined from site investigation and soil exploration program on site of Elektrenai power plant, Lithuania. Geological investigation involved boreholes (BH), cone and dynamic penetration tests (PT) and trial pits (TP). Totally 8 boreholes of the depth of 30 m and other 45m-deep, were drilled. Soil samples were taken from trial pits in order to determine granulometric composition, plasticity and Proctor density. 21 tests of cone penetration (CPT) of the depth of up to 15 m were carried out. At 4 points below 15 m precise measurement of pore pressure have been carried out (CPTu). There were 16 dynamic penetration (DPSH) tests performed in the depth of up to 25–35 m. XIII engineering geological layers (EGL) were determined in investigation area based on investigation data of CPT and DPSH of boreholes, excavations and soil as well as laboratory investigations.

Surface of investigation site was leveled and the major part of area was replaced with manmade soil (tplIV) consisting of silty sand (SU, SUo), low plasticity clay (TL), intermediate plasticity clay (TM), silty clay (TU) and gravel sand (GU). The thickness of manmade soil layer ranges from 0.5 m to 2.20 m with the altitudes ranging from 96.0 m to 97.9 m. The depth of the limnoglacial sediments ranges from 13.20 m to 15.80 m. The altitudes of the layer sole ranges from 82.14 m to 84.93 m of altitude. Below that, the silty sand (SU, SUo) was present to 67.7 m of altitude.

From the investigation of engineering geological layers, four geological layers were generalized:

1. Medium to firm clay sediment, TU, TL, TM (the depth of this layer is up to 15 m from surface)
2. Medium to coarse silty sand, dense (the depth of this layer is up to 19 m from surface)
3. Medium to coarse silty sand, medium dense (the depth of this layer is up to 25 m from surface)
4. Medium to coarse silty sand, very dense (the depth of this layer is up to 30 m from surface)
5. These four layers were used in the design and calculations of piling foundation [11]

These four layers were used in the design and calculations of piling foundation. Description of these layers is presented in Fig. 1.

In our case ϕ' is derived from SPT results which were obtained from DPSH test and described in Table 1. To apply DPSH data, the N20 DPSH data were converted to N30 SPT values, where N is the blow count recorded in an standard penetration test [9]. According to Eurocode 7, N30 were corrected to (N1)60. Although the SPT is not considered as a refined and completely reliable method of investigation, the N values give useful information with regard to consistency of cohesive soils and relative density of cohesionless soils. The accepted values of shearing resistance ϕ' together with values of unit weight for the active zone are presented in Table 1.
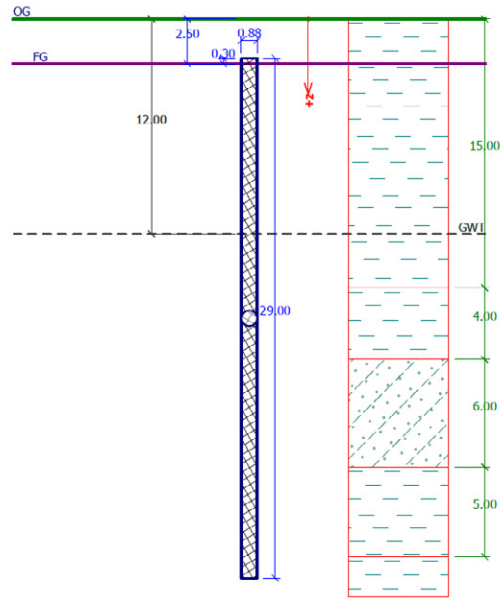
Fig. 1. Geotechnical profile of the site where gas turbine is planned

Table 1. Unit weight and shearing resistance values of subsoil structure

Layer	Levels (m)	Lithology	γ' (kN/m³)	Thickness (m)	$\phi°$ (*) obtained from direct shear testing
1a	98–95	Clayey deposit, medium to firm consistency ↑GWL	19.5	3	$10°^{(*)}$
1b	95–83	Clayey deposit, medium to firm consistency ↓GWL	5.2	12	$10°^{(*)}$
2	83–79	Medium to coarse slightly silty sands, dense	12.2	4	$32°$
3	79–73	Medium to coarse slightly silty sands, medium dense	11.2	6	$30°$
4	73–69	Medium to coarse slightly silty sans, dense to very dense.	12.2	4	$34°$

4. Estimation of immediate settlements of bored piles foundation

4.1. Estimation of immediate settlements employing analytical method

Total settlement can be assessed as the sum of the axial and the point settlement. For a conservative end-bearing behavior, considering low or negligible contribution of shaft resistance [1]:

$$S_p = \frac{Q \cdot L}{A \cdot E_p} + q \cdot D \cdot \frac{1 - \mu^2}{E_s} \cdot mI_s \cdot I_F \cdot F_1 \tag{1}$$

The first term (before the sum sign) on right-hand side of the Eq. (1) described the average pile axial settlement for pile length, L, average cross-section area, A, and an elastic modulus of the pile, E_p. Length, L, is estimated to be 67% and 100% of the total pile length, taking 100% at clayey part and 75% at embedment sand. It is equal to 18.2 m. Elastic pile modulus, E_p, is determined according to the cylinder compressive strength f_{ck} (for f_{ck} = 30 MPa, E_p = 32.000 MPa). Maximum applied load at pile head, Q, is equal to service working load of Q = 2239 kN.

The second term in the Eq. (1) describes the point settlement, which depends on pile load, q, representing pile bearing pressure at a point. It is equal to input load divided by A_p, i.e., 4450 kPa. Stress-strain modulus of soil below the pile point, E_s, is obtained from: for the dense and very dense sands with $N_{20}>30 \rightarrow N_{30}>50$ it equals E_s >100 MPa. Poisson ratio for sand soil, μ, equals to 0.3, while shape factor, mI_s, equals to 1.0. Embedment factor, I_F, has value of 0.50, because pile

length, L, and diameter, D, ratio is larger than 5. Reduction factor, F_1, was set to 0.75, since point bearing and considering some skin resistance.

According to Eq. (1) the total value of settlement, S_p, was estimated to be equal to 15.6 mm. This value could be considered as maximum, obtained from the conservative side, based on end-bearing behavior of the pile.

Pile settlement analysis showed that total expected maximum settlement value was 15.6 mm. It includes 2.1 mm settlement of pile deformation from vertical compressive loads. For such structure, foundation settlement should not be more than 2% of pile diameter. For the pile of 880 mm diameter, the foundation settlement should not be more than 16 mm. The calculation shows, that for pile of diameter 880 mm, the necessary length was 29 m. Such length is sufficient to endure overall load.

4.2. Estimation of immediate settlements employing program Pile CPT (Geo5) and Plaxis 3D Foundation

The computing settlements of bored piles foundation superstructure was carried out employing geotechnical engineering package Pile CPT from Geo5 software. The magnitude of pile head settlement s_d is calculated by Eq. (2):

$$s_d = s_{toe,d} + s_{el,d} \tag{2}$$

where: $s_{toe,d}$ is a pile toe settlement due to acting forces, consisting from two components: pile toe settlement due to force acting at toe ($s_{toe,d,1}$), and pile toe settlement due to force acting on the shaft ($s_{toe,d,2}$); $s_{el,d}$ is a pile settlement due to elastic compression. The magnitudes of settlements $s_{toe,d,1}$ and $s_{toe,d,2}$ are determined from built-in graphs according to the NEN 6743 standard, which allows to determine:

1. Pile settlement due to toe vertical force (pile settlement in percentage of the equivalent pile diameter plotted as a function of the toe vertical force given in percentage of the maximum toe resistance q_t)
2. Pile settlement due to shaft force (pile settlement in mm plotted as a function of the shaft force given in percentage of the maximum shaft resistance f)

The pile settlement analysis was carried out according to the following standards and approaches: EN 1997-2, NEN 6743, Schmertmann and finite element method applied in Plaxis 3D Foundation package.

In program Pile CPT settlement analysis is performed according NEN 6743 standard, where pile toe and pile shaft forces are given. Whiles partial factor on base resistance and partial factor on shaft resistance were involved in calculations (partial factor on base resistance γ_b is equal to 1.6, partial factor on shaft resistance γ_s is equal to 1.3).

As a result, the analysis provides the limit loading curve, which describes the variation of vertical load, Q, as a function of the pile settlement, s. Fig. 2 shows a shape of the limit loading curve for a given problem according to EN 1997-2 method.
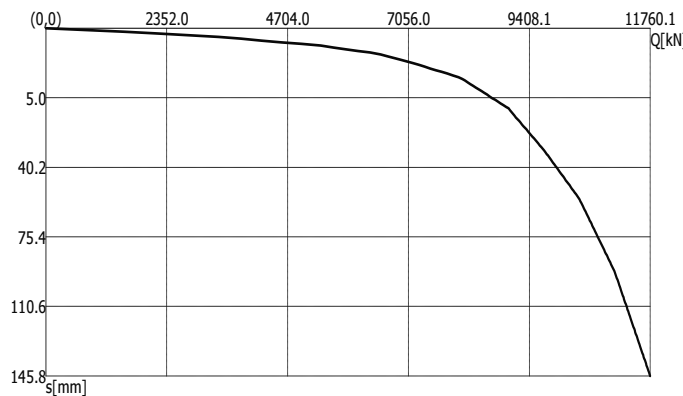

Fig. 2. Ultimate load transfer curve (EN 1997-2)

Plaxis 3D Foundation is the finite element package intended for the three-dimensional deformation analysis of foundation structure. The elastic-plastic Mohr-Coulomb model was used, which involves five input parameters, i.e. E and ν for soil elasticity; φ and c for soil plasticity and ψ as an angle of dilatancy. This Mohr-Coulomb model represents a first-

order approximation of soil. For each layer one estimates a constant average stiffness. Due to this constant stiffness, computations tend to be relatively fast and one obtains a first estimation of deformations.

Comparison results, obtained by different methods, are presented in Table 2.

Table 2. Comparison between results obtained by different methods

Method	Pile length, m	Immediate settlement, mm
Bowles	29	15.9
Schmertmann	29	7.2
EN 1997-2	29	6.5
NEN 6743 Limit state 1B	29	5.3
NEN 6743 Limit state 2	29	5.4
FEM (Plaxis 3D Foundation)	29	5.9

4.3. Static load pile test

On the construction site one test pile and four reaction piles were prepared. The cast-in-place bored piles have been manufactured using Bauer equipment by Skanska EMV Ltd in October 2007. The test pile is made on 6th October. The diameters of the test and reaction piles are 880 mm. The length of test pile is 28.6 m. Concrete type is C30/37. Steel reinforcement cage is made from main bars 10 pcs. Ø20 mm, over full pile length and transverse bars Ø12 mm, step 0.15 m. The outer diameters of the reinforcement cages is 680 mm, the longitudinal bars are distributed eventually along the perimeter. The pile head (1.5 m) is strengthened with a tubular casing.

The testing equipment consists of the following parts:

1. Two 12 m length steel trusses, having the total bearing capacity $2 \times 3000 = 6000$ kN. The trusses are connected with tension piles by welding and bolts
2. One 4.5 m length steel beam having the bearing capacity 6000 kN
3. Hydraulic jack with electrical oil pump. Maximum load of the jack is 5650 kN
4. Dial gauges with accuracy 0.1 mm for measurement of pile top displacements. The displacements of the compression pile have been measured with four and the displacements of the every tension piles with two gauges. The gauges were connected with piles by steel wire
5. Reference beams for dial gauges. The length of reference beams was between 6 to 8 m and these were supported on the ground

The testing procedure was carried out according to Iberdrola's "Method statement for testing preliminary pile" [10].

The static load pile test was performed gradually increasing the load. The test was started at 10:00 in the morning and every each hour (beginning from 12:00 hour) the load was increased by 250 kN. The basic design load Q (2500 kN) was reach after 12 hours. The settlement value was 5.2 mm. Fig. 3 shows a shape of the load-settlement curve of static load pile test.
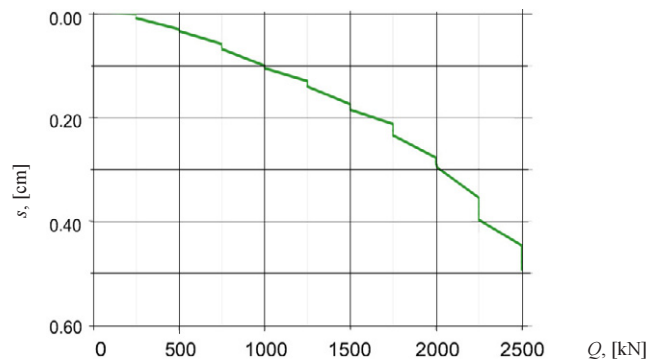

Fig. 3. Load – settlement curve of static load pile test

Fig. 4 shows a shape of the time-settlement curve for the static load pile test. The green curve represent experimental results of static load pile test, the blue curve – the calculations results obtained by employing finite element method of Plaxis 3D Foundation package.
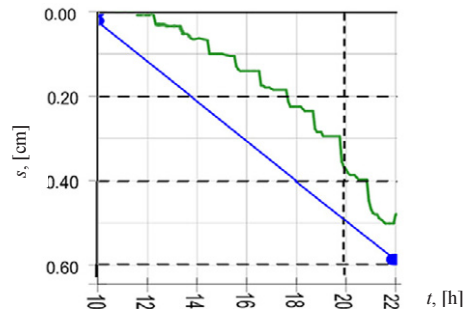

Fig. 4. Time – settlement curve of static load pile test

5. Conclusions

The pile settlement analysis was performed employing most widely used standards and approaches, namely EN 1997-2, NEN 6743, Schmertmann and Bowles, and finite element method. The comparative analysis of five methods indicates that the settlement values are similar for all considered methods. The largest value of bored pile settlement was obtained employing analytical Bowles method. The reliable results of pile settlements were obtained from finite element method of Plaxis 3D Foundation package and employing method using Pile CPT package from Geo5 software. The EN 1997-2 ultimate limit stage method is the most appropriate for this project due to the geotechnical structure and the reliability of DPSH against CPT data in the lower sandy levels. The choice of appropriate safety factors for this specific foundation type is also important considering remarks from EN 1997-2 and Tomlinson criteria [13]. Bowles' settlement criterion is suitable for this analysis as conservative limit, considering that the real settlement should be lower than estimated value.

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